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THE ANALYSIS OF DEBRIS DATA FROM UK/AUSTRALIAN SMALL QUANTITIES BRICK CUBICLE TESTS

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ABSTRACT

A UK/Australian test programme to determine the effects from the detonation of quantities of explosives in brick wall cubicles is described elsewhere. In this paper the debris pickup data is analyzed to determine predicted Inhabited Building Distances (IBD) and fatality probability vs distance relationships which might be used in advice on the storage of explosives and in the development of risk assessment models.

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INTRODUCTION

1. Current UK ESTC Quantity-Distance (QD) rules dictate that, for quantities of Hazard Division (HD) 1.1 explosives less than 1000kg, minimum Inhabited Building Distances (IBD) of 400m or 270m are to be maintained in the light of hazard from fragments or building debris. Quite clearly, where much smaller quantities of explosives are stored, the fragment hazards will be lower at any given range. The normally accepted lethal fragment density for IBD of $1/55.7m^2$ will be achieved at a much shorter range if the number of rounds or size of rounds in the donor stack is reduced. To gain maximum economic benefit from storage of small quantities it is essential to be able to quantify the way in which the potential consequences of an explosives event are related to the quantity of explosives involved and also to the way in which they are stored.

2. In 1993 the UK Services, at a special workshop, identified a significant economic need for a better understanding of debris throw from small brick buildings as the result of internal small quantity explosions. At about the same time the Australian Ordnance Council identified very similar needs and the UK ESTC Support Group agreed with them a joint programme of tests to address these needs. The work was to be carried out under the terms of the Memorandum of Understanding on Research existing between the two nations.

3. The programme of work and its current status are described briefly below and will be expanded upon separately at the conclusion of the programme. This paper takes the results of debris data from the first phase and makes an initial attempt to develop from it useable consequence models for consideration for use in ESTC and NATO prescriptions and in risk assessment modelling. The form and detail of the models developed are almost certain to be refined as a result of the remaining test series. These remaining tests took place in April/May 1996 and the results are currently being analysed.

THE TEST PROGRAMME

4. The test programme, defined in Reference 1, was designed to try and quantify the explosion effects from relatively small explosions in brick buildings. The effect of frangible roofs vs concrete roofs, English bond, solid brick walls (EBSB) vs Double brick cavity spaced (DBCS) walls and traversing were to be investigated. A special building designed by the UK Defence Work Services in which brick faces are built into a linked concrete frame was also included. A cubicle with dimensions 3m x 3m x 2.4m was chosen and three charge weights, 50, 25 and 10kg of Composition B were to be used. Table 1 shows the overall test plan. For economic reasons it was necessary to carry out the tests in two phases, one in April/May 1995 and, the second in the same period of 1996. In Table 2 the tests completed in Phase 1 are listed.

TRIALS DETAILS

5. Buildings were erected in accordance with the specification (Reference 1) on reinforced concrete bases. Reinforced concrete roofs were cast on the ground and then lifted into place after the brick walls had time to cure. Frangible roof buildings were fitted with expanded steel security meshes below the wood and tarred felt roof. Standard steel faced solid wood doors were fitted and closed using external bolts.

6. Pressure measurements both inside and outside the buildings were made using gauges set into the walls and the ground in front of the door. Cine and video records of each firing allowed the measurement of roof and some debris (eg door) velocities and in addition gave valuable evidence of the way in which the walls were projected. Doppler radar was used to measure the initial wall movement as explosion products prevented the use of video during the first 500ms or so.

7. Around each building a full 360^{o} search area was marked in 10^{o} x 20m segments out to 300m. Figure 1 shows the disposition of the ground grid relative to the sides of the buildings and their traverses. Each zone was identified by direction defining letter(s) and the range to the zone centre point, eg A70 or JJ150. After each firing a team of about 30 people searched this area and collected all building debris. Within the centre 20m circle the debris was collected in bulk and weighed using a weigh bridge. Beyond that circle debris was collected by 10^{o} x 20m zone and then sorted, counted and recorded as described below.

DEBRIS ANALYSIS

8. Debris was firstly separated into "lethal" and "non-lethal" sizes. The guideline for this was

> "debris with any dimension greater than or equal to 50mm will be considered potentially lethal".

The decision to use this criterion was based on the generally accepted potentially lethal debris minimum energy of 80J and a best estimate initial debris speed of 30ms^{-1}; the weight of brick necessary to achieve 80J at this velocity being equivalent to a 50mm cube. Thus a degree of conservatism was built in with the need for only one dimension needing to exceed the 50mm. The number of potentially lethal debris in each zone was then recorded. All debris in the zone was then weighed and aggregated with the weight from the centre zone to determine an approximate collection efficiency (ie total weight collected/theoretical weight of the building). For the buildings with concrete roofs, concrete debris was recorded separately to brick. However the data analysis has been carried out on the combined brick and concrete densities.

9. As debris projected in any direction and collected at a given radial zone had passed

through the radial zones closer in it clearly contributed to the debris density of all the zones through which it passed. It is acknowledged that some conservatism is built into this approach due to some debris passing through zones at above head height. This particularly applies to concrete debris from roofs. Debris numbers were therefore accumulated along radii in accordance with what is now known as the Trajectory Normal Method (Reference 2). Debris densities for each zone were then calculated. The variation in effect as a function of azimuthal angle was quantified by considering the range at which the debris density fell to 1 per $55.7m^2$, the density generally accepted as defining the Inhabited Building Distance (IBD). A plot of this value vs azimuth for each of the six tests are given in Figures 2 to 7. A similar plot for the concrete roof in Test 3 is shown in Figure 8.

10. From a risk assessment viewpoint it is essential to be able to determine the effect of the debris in terms of Fatality Probability (P_f) as a function of range. Given the debris density for a specific area, this is calculated as follows:

Expected number of hits (on a standing person)

$$NE_H = 0.56 \text{ x Debris Density}$$

where $0.56m^2$ is the presented area of the person

Probability of fatality (ie the probability of at least one hit)

$$P_F = 1 - \exp(-NE_H)$$

11. As can be seen from Figures 2 to 8 the debris densities are high along the normals to the walls compared with the intermediate directions. Initially a "mean" fatality/range relationship was generated by averaging the fragment densities over the full 360^o azimuth in each radial annulus. The results of these calculations and a straight line outer (conservative) envelope are shown in figure 9. However, in the directions normal to the walls this relationship would lack conservatism. To generate a simple, more conservative model it was decided to take the three highest fragment counts in the 20-40m zones around each of the four directions normal to the walls, divide them into traversed and non-traversed sets and devise fatality/range curves based on the mean area densities calculated as follows

$$\text{mean debris density} = \frac{\text{total debris count in 6 zones}}{\text{area of the 6 zones at that radius}}$$

12. In Figure 10 data from all tests are plotted. The separated traversed and untraversed fatality envelopes are highlighted. These have been generated by joining the extreme right hand points of each data set with a straight line. Clearly the most conservative enveloping function will be that for the untraversed data set. Traversing reduces the fatality at any given range by approximately one half of an order of magnitude.

13. Figure 11 shows the sub-set of the data for concrete roof buildings and includes both brick and concrete debris. It demonstrates that the increase in charge size from 25kg to 50kg moves the fatality probability curve to the right whether or not the traverse is there.

14. Figure 12 shows the comparable data for buildings with frangible roofs. Comparison of Figures 11 and 12 shows that the confinement of the concrete roof and consequent effect of the quasistatic pressure results in considerably enhanced debris throw and hence increased fatality probability at a given range.

15. Figures 13 and 14 illustrate the effects of the use of cavity rather than solid walls. There is disparity between the results for 50kg and 25kg charges. For the 25kg charge the dispersion of debris is greater for the cavity walls than for the solid whereas in the case of the 50kg charge the effect is reversed and, in general, very much smaller. As can be seen from Figure 15 the untraversed curve for the 25kg charge provides the straight line outer envelope for all eight curves.

DISCUSSION

Inhabited Building Distance

16. Reference to Figures 2 to 8 shows visually the significant effects of the changes in debris throw produced by the parameter variations covered in the test programme. The IBD distances at which the debris density in any given direction falls to 1 per 55.7m^{-2} vary as a function of azimuthal angle and, as might be expected, are largest in the principal directions normal to the walls of the test structure. Between the principal directions the density of debris falls somewhat erratically and there is debris thrown even in the direction of the building corners. This variability led to the conclusion that IBD could be best defined by outer enveloping the azimuthal distributions with a uniform IBD equal to the largest calculated in the principal directions. The traverses consistently reduce the IBD but are not totally effective, reductions of 30% to 50% being typical and a further refinement of the IBD definition may be made by adopting uniform traversed and untraversed figures. The dividing line between them could be the line of the structure diagonals. The IBD distances for the 6 situations tested are given in Table 3.

17. The largest IBDs are those for the concrete roof buildings and reflect the effect of the quasistatic pressure being contained within the building rather than, as in the case of the frangible roof buildings, being vented very early in the explosion. This is also illustrated by wall velocity measurements where the initial velocity of the walls of concrete roof buildings are 2-3 times those with frangible roofs. In view of the significant differences in IBD further refinements in IBD definition are made by differentiating between frangible and concrete roof structures. The advisability of making any more detailed refinements is questioned on the basis that all test situations are unique and knowledge of the statistical significance of the individual test data is minimal.

18. In all the tests the loading density of the explosives in the structures was no greater

than $2.3kgm^{-3}$. It is known that the loading density will play a part in the way debris is generated and projected. In tests 3 and 4 it can be seen that IBD is increasing with loading density (ie in the increase from 25kg to 50kg charge in identical buildings). In view of the unknown nature of the variation beyond the maximum density tested the IBDs adopted should be limited to situations in which the loading density is below $2.3kgm^{-3}$.

19. Therefore, it is proposed that, for Net Explosives Quantities up to 50kg at loading densities no greater than $2.3kgm^{-3}$, Inhabited Building Distance should be 172m for untraversed and 153m for traversed sides of concrete roof buildings. For frangible roof buildings the untraversed distance should be 134m and traversed distance 107m.

Fatality Probabilities for Risk Assessment Modelling

20. In consideration of the azimuthal variability, coupled with the need for conservatism in the definitions of fatality probabilities, the use of the debris densities only in the principal directions has been adopted. Whilst it would be feasible to generate directionally dependent fatality probabilities, for the reasons stated earlier regarding IBD refinement this is not thought wise. The proposals for fatality probability/range relationships follow therefore those for IBD.

21. The straight line envelopes of fatality probability shown in Figures 10 - 12 and 15 form conservative boundaries to the test data. The most conservative approach will be the use of the untraversed envelope for concrete roof buildings (Figure 11). Differentiation between traversed and untraversed walls can then be introduced by again taking the relevant envelopes for concrete roof buildings (Figure 11). Furthermore the difference between frangible and concrete roof structures can then be accounted for by the use of the additional envelopes for frangible roof structures (Figure 15). It has to be emphasised again that, with the use of the more refined envelopes, confidence in the fatality probabilities will be reduced and any further refinement beyond that described is inadvisable.

22. The same NEQ and loading density limitations of 50kg and $2.3kgm^{-3}$ will apply to the fatality probability data.

23. The equations of the fatality probability envelopes recommended for use for risk assessment modelling are given in Table 4 and shown graphically in Figure 16.

CONCLUSIONS

24. Interim Inhabited Building Distances and Fatality Probability/Distance relationships for small quantity(<=50kg) explosions in brick wall buildings can be defined from tests carried out at Woomera, Australia. Completion of the processing of the remaining Woomera tests and those conducted in UK may result in further refinement of the analysis and recommendations.

25. As the density of debris varies as a function of azimuthal angle relative to the walls of the structure, to maintain conservatism only the densities in the principal directions normal to the walls are used in the calculations.

26. Whilst the tests covered a number of parametric variations, it is concluded that, for statistical confidence reasons, it is sensible to use only the enveloped results for traversed and untraversed concrete and frangible roof structures.

27. Inhabited Building Distances and Fatality Probability/Range relationships recommended for use are those given in Paragraph 19 and Table 4.

FUTURE WORK

28. Tests carried out at DTEO Shoeburyness have still to be analyzed and the data incorporated.

29. The analysis of the second phase of the tests in Australia is continuing.

REFERENCES

1. Explosion Effects - Small Quantity ESH Trials, Ref AUS ESTC 90/21185 of 24 August 1993.

2. Procedures for the Analysis of the Debris Produced by Explosion Events, M M Swisdak, Paper to 24th DoD Explosives Safety Seminar, August 1990

TABLE 1 PROPOSED JOINT AS/UK SMALL QUANTITY ESH FRAGMENTATION TRIALS

SERIAL	BUILDINGS/COMMENT	NEQ (kg)
1.	DBCS[1] frangible roofed ESH untraversed, charge to be centrally located[3].	10kg HD 1.1 (non-fragmenting) (nf)
2.	DBCS frangible roofed ESH untraversed, charge to be located 1.0 m above floor and 0.5 m from wall opposite door.	10 kg HD 1.1 (nf)
3.	EBSB[2] frangible roof - semi traversed	25 kg HD 1.1 (nf)
4.	DBCS frangible roof - semi traversed	25 kg HD 1.1 (nf)
5.	As for serial 3	50 kg HD 1.1 (nf)
6.	As for serial 4	50 kg HD 1.1 (nf)
7.	EBSB reinforced concrete roof - semi traversed	25 kg HD 1.1 (nf)
8.	DBCS reinforced concrete roof - semi traversed	25 kg HD 1.1 (nf)
9.	As for serial 7	50 kg HD 1.1 (nf)
10.	As for serial 8	50 kg HD 1.1 (nf)
11.	RC Column Heavy Roof - semi traversed	25 kg HD 1.1 (nf)
12.	RC Column Heavy Roof - semi traversed	50 kg HD 1.1 (nf)

NOTES

1. DBCS = Double Brick Cavity Spaced Walls
2. EBSC = English Bond Solid Brick Walls
3. The stand-off was later reduced to 150mm to equate to similar tests in concrete roof buildings carried out in UK.

TABLE 2 TEST DETAILS FOR THE FIRST TEST PHASE

TEST NO	WALL TYPE	WALL THICKNESS	ROOF TYPE	NEQ kg
1	ENGLISH BOND SINGLE BRICK	230mm	FRANGIBLE	50
2	ENGLISH BOND SINGLE BRICK	230mm	FRANGIBLE	25
3	ENGLISH BOND SINGLE BRICK	230mm	CONCRETE	50
4	ENGLISH BOND SINGLE BRICK	230mm	CONCRETE	25
5	DOUBLE BRICK CAVITY SPACED	270mm	FRANGIBLE	50
6	DOUBLE BRICK CAVITY SPACED	270mm	FRANGIBLE	25

TABLE 3 SUGGESTED INHABITED BUILDING DISTANCES FOR THE 6 TEST CONDITIONS

TEST NO	UNTRAVERSED IBD (M)	TRAVERSED IBD (M)
1	122	90
2	111	71
3	172	153
4	140	125
5	132	96
6	134	107

TABLE 4 EQUATIONS OF FATALITY PROBABILITY ENVELOPES RECOMMENDED FOR USE IN RISK ASSESSMENT MODELLING

ROOF TYPE	TRAVERSED/ UNTRAVERSED	EQUATION OF FATALITY PROBABILITY ENVELOPE
CONCRETE	UNTRAVERSED	LOG10(P(F))=1.589116-0.02103579R
CONCRETE	TRAVERSED	LOG10(P(F))=1.239435-0.02217850R
FRANGIBLE	UNTRAVERSED	LOG10(P(F))=1.118456-0.02364092R
FRANGIBLE	TRAVERSED	LOG10(P(F))=0.781937-0.02520135R

FIGURE 1 DISPOSITION OF THE TEST BUILDINGS RELATIVE TO THE DEBRIS COLLECTION GRID

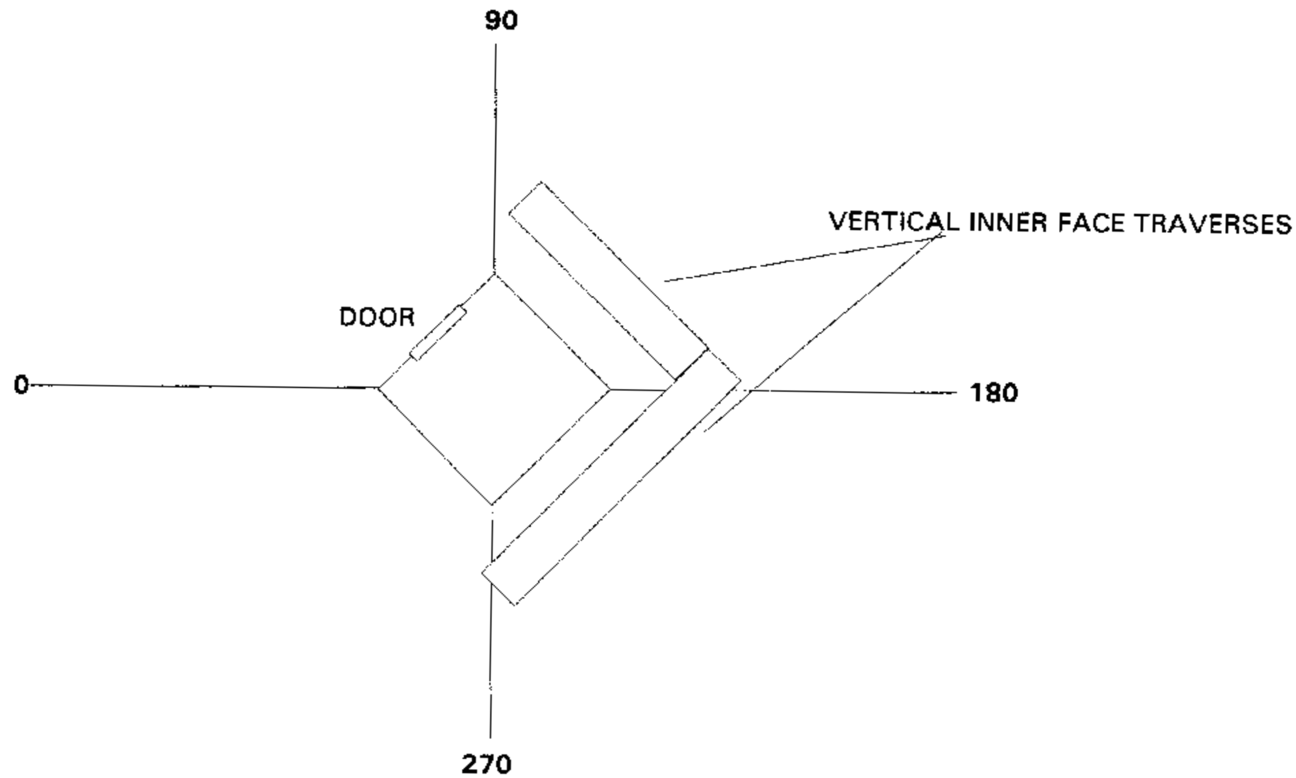

FIGURE 2 TEST 1: RANGE TO ONE LETHAL FRAGMENT PER 55.7SQM AS A FUNCTION OF DIRECTION

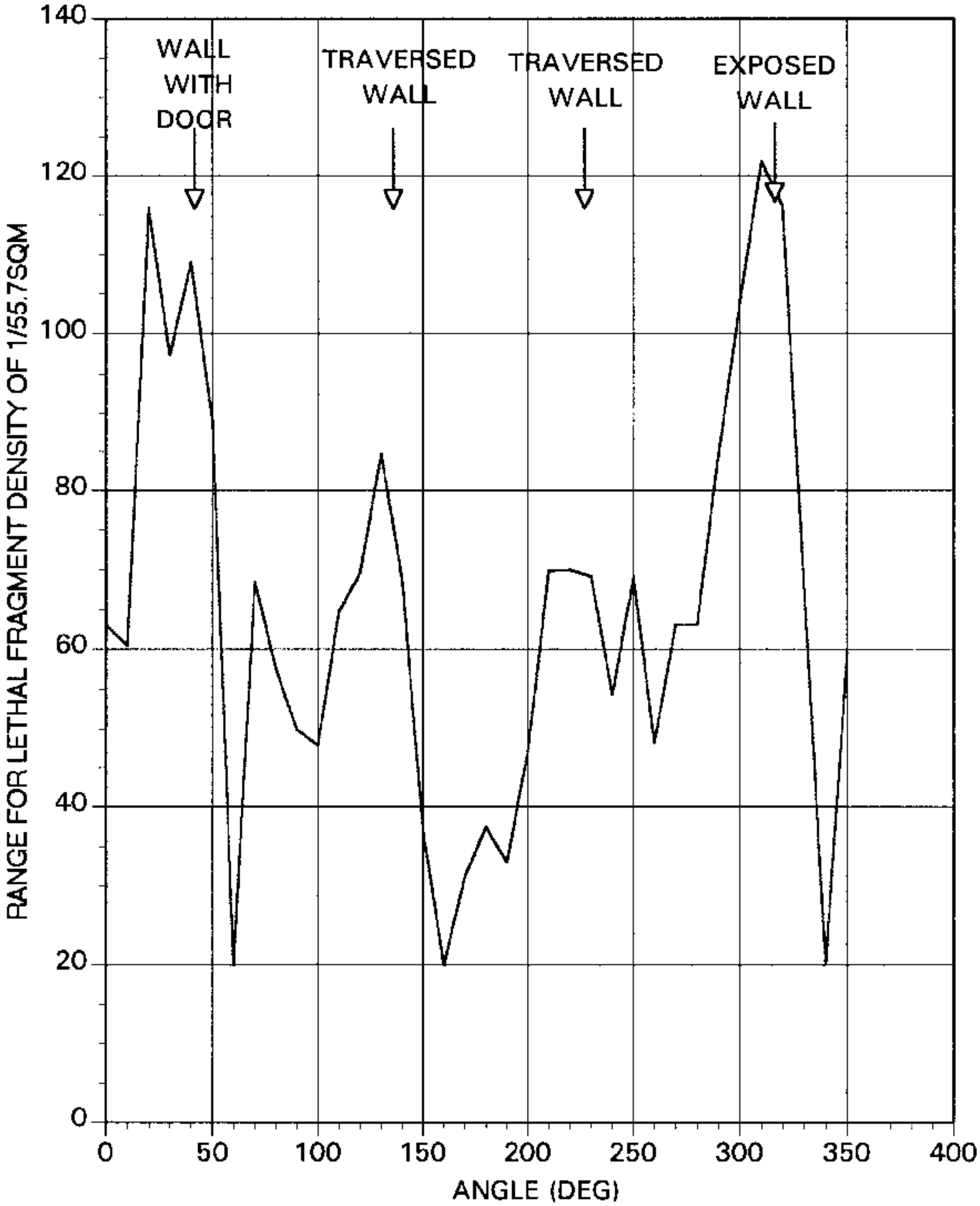

FIGURE 3 TEST 2: RANGE TO ONE LETHAL FRAGMENT PER 55.7SQM AS A FUNCTION OF DIRECTION

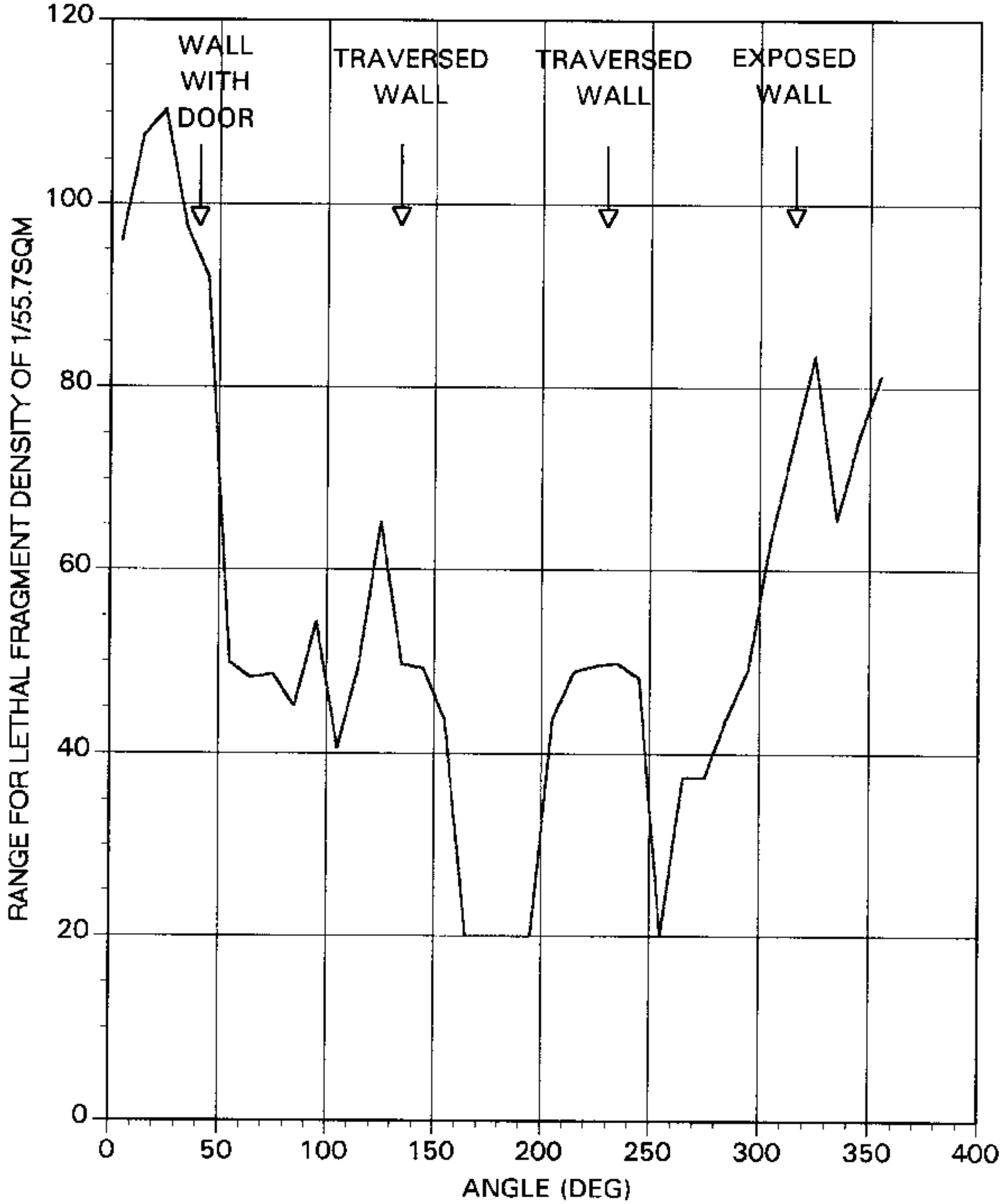

FIGURE 4 TEST 3: RANGE TO ONE LETHAL FRAGMENT PER 55.7SQM AS A FUNCTION OF DIRECTION

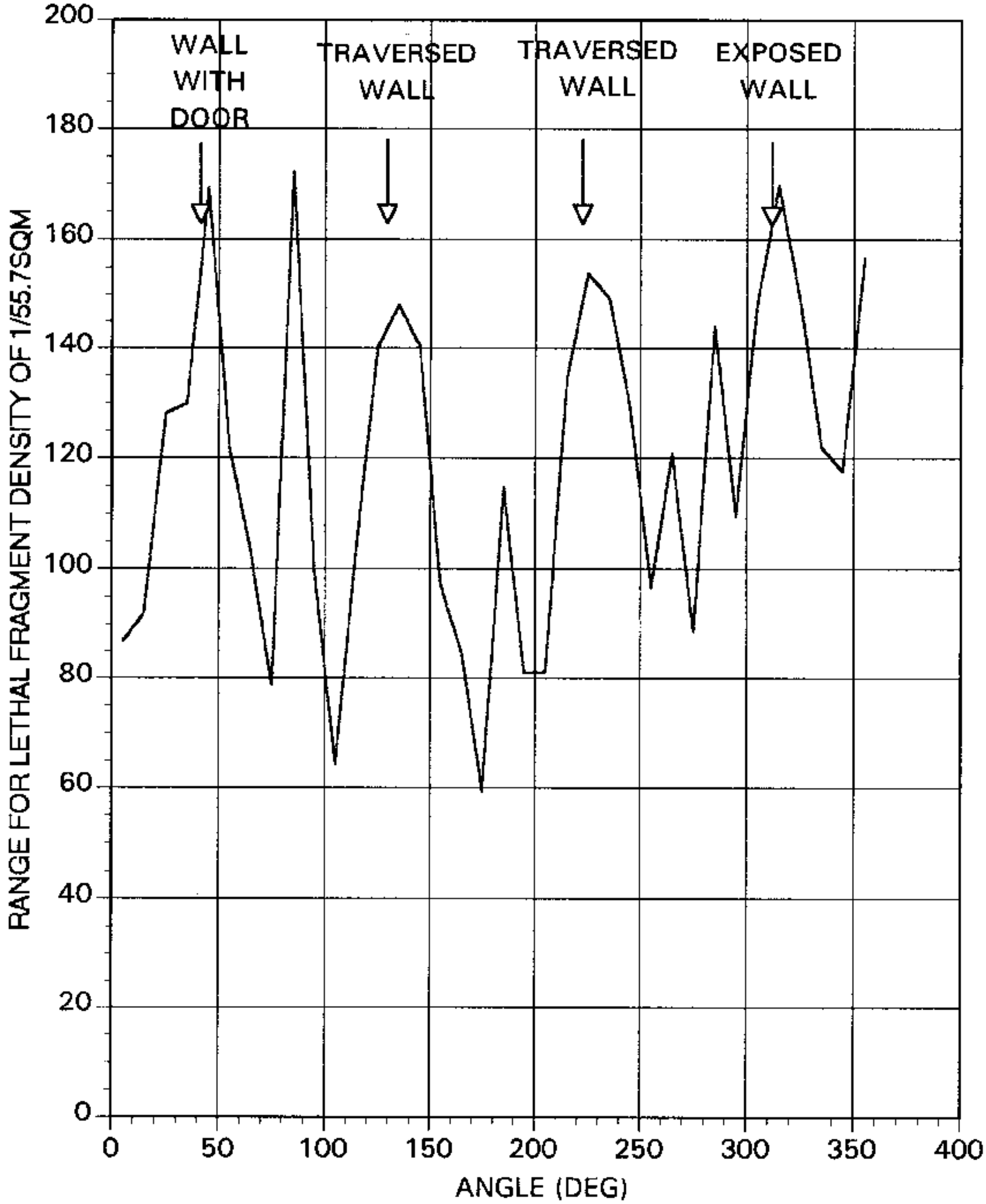

FIGURE 5 TEST 4: RANGE TO ONE LETHAL FRAGMENT PER 55.7SQM AS A FUNCTION OF DIRECTION

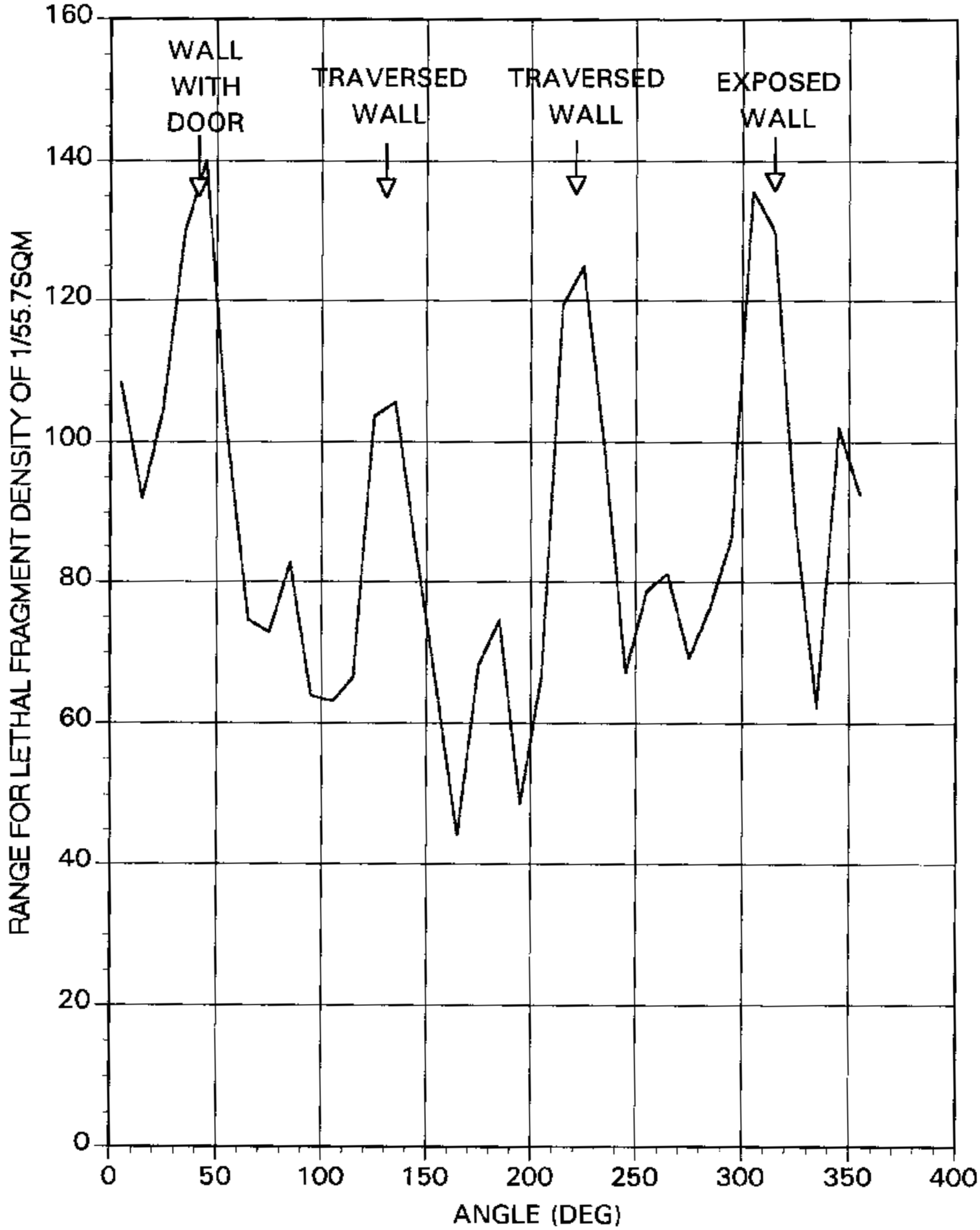

FIGURE 6 TEST 5: RANGE TO ONE LETHAL FRAGMENT PER 55.7SQM AS A FUNCTION OF DIRECTION

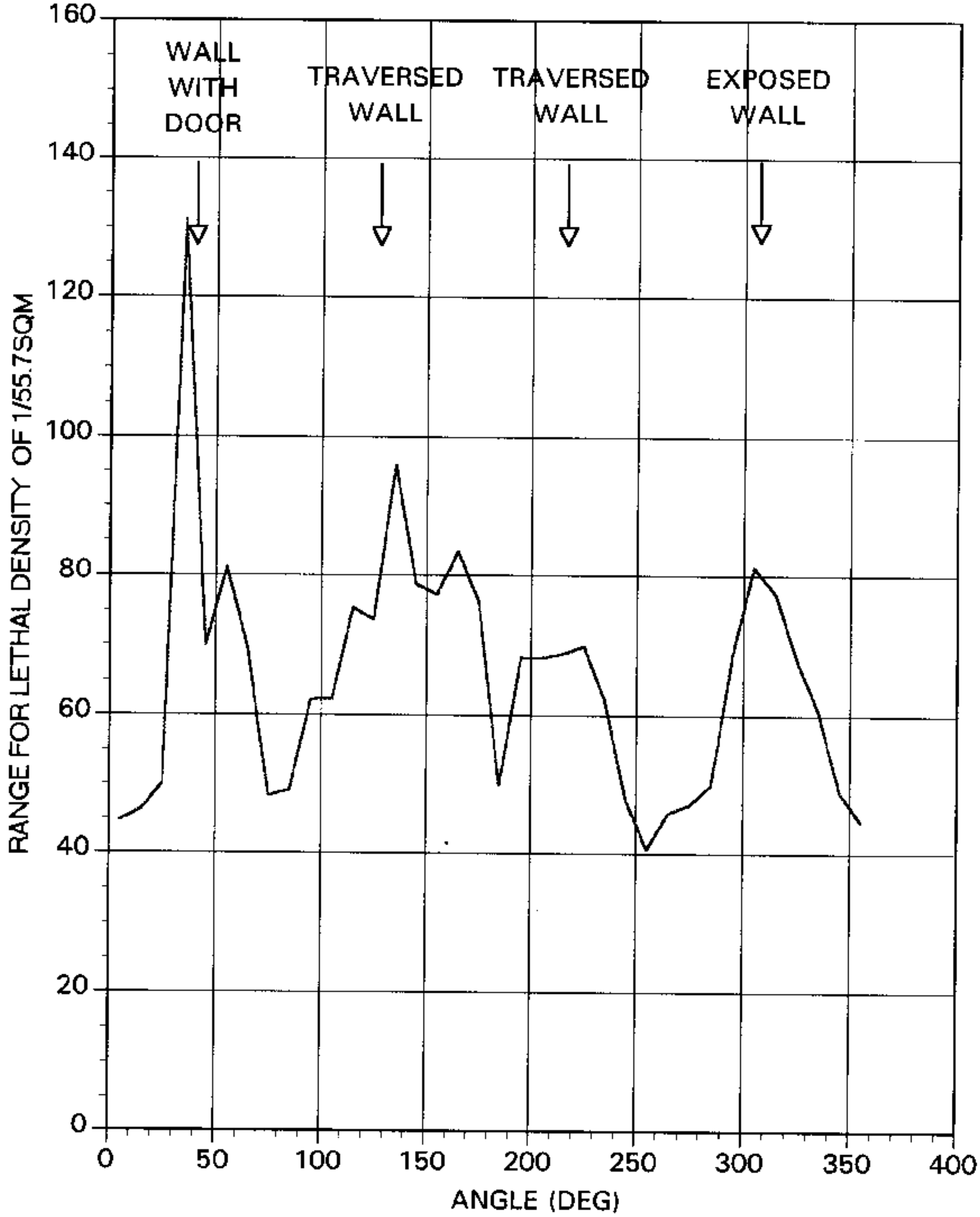

FIGURE 7 TEST 6: RANGE TO ONE LETHAL FRAGMENT PER 55.7SQM AS A FUNCTION OF DIRECTION

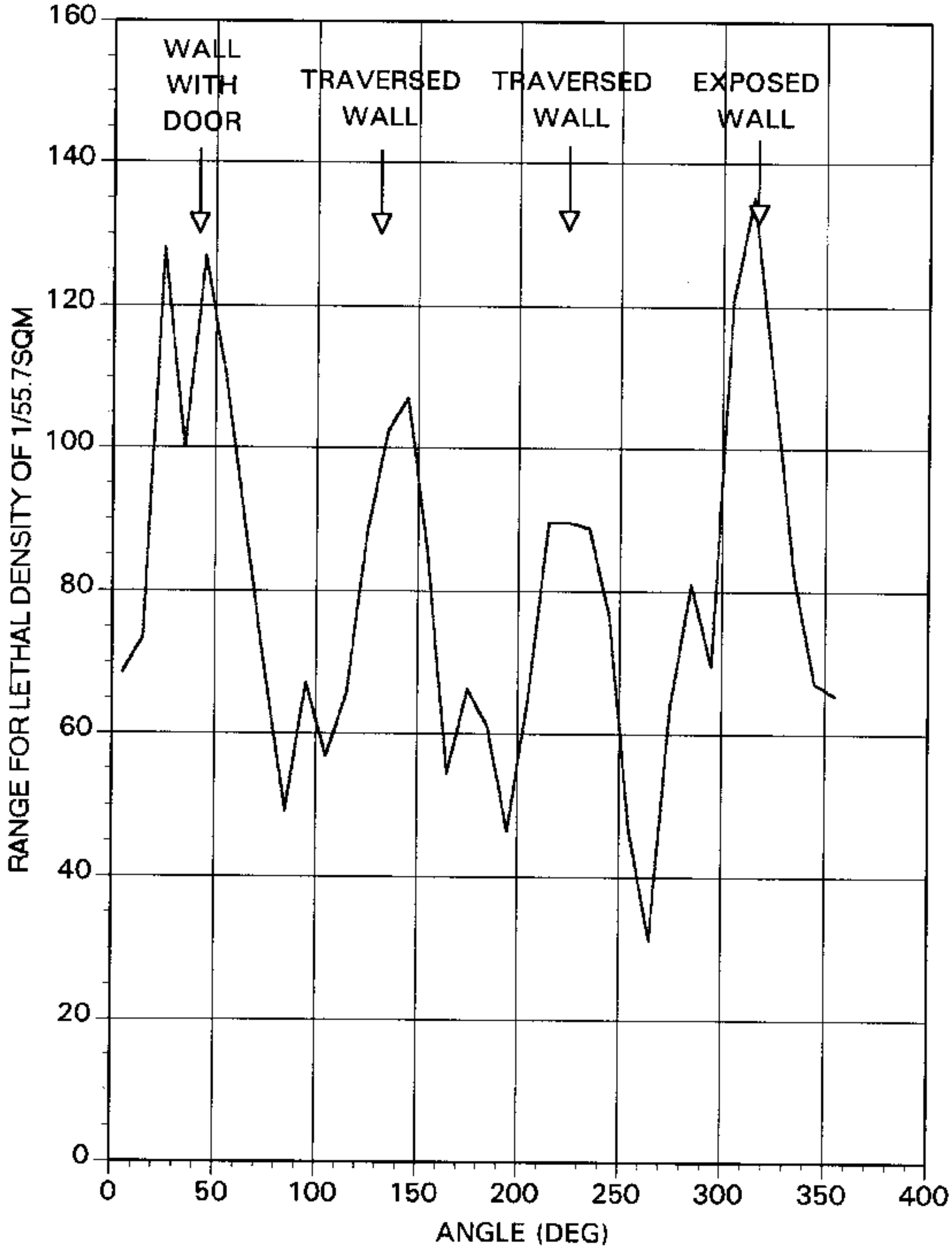

FIGURE 8 TEST 3 CONCRETE ROOF: RANGE TO ONE LETHAL FRAGMENT PER 55.7SQM AS A FUNCTION OF DIRECTION

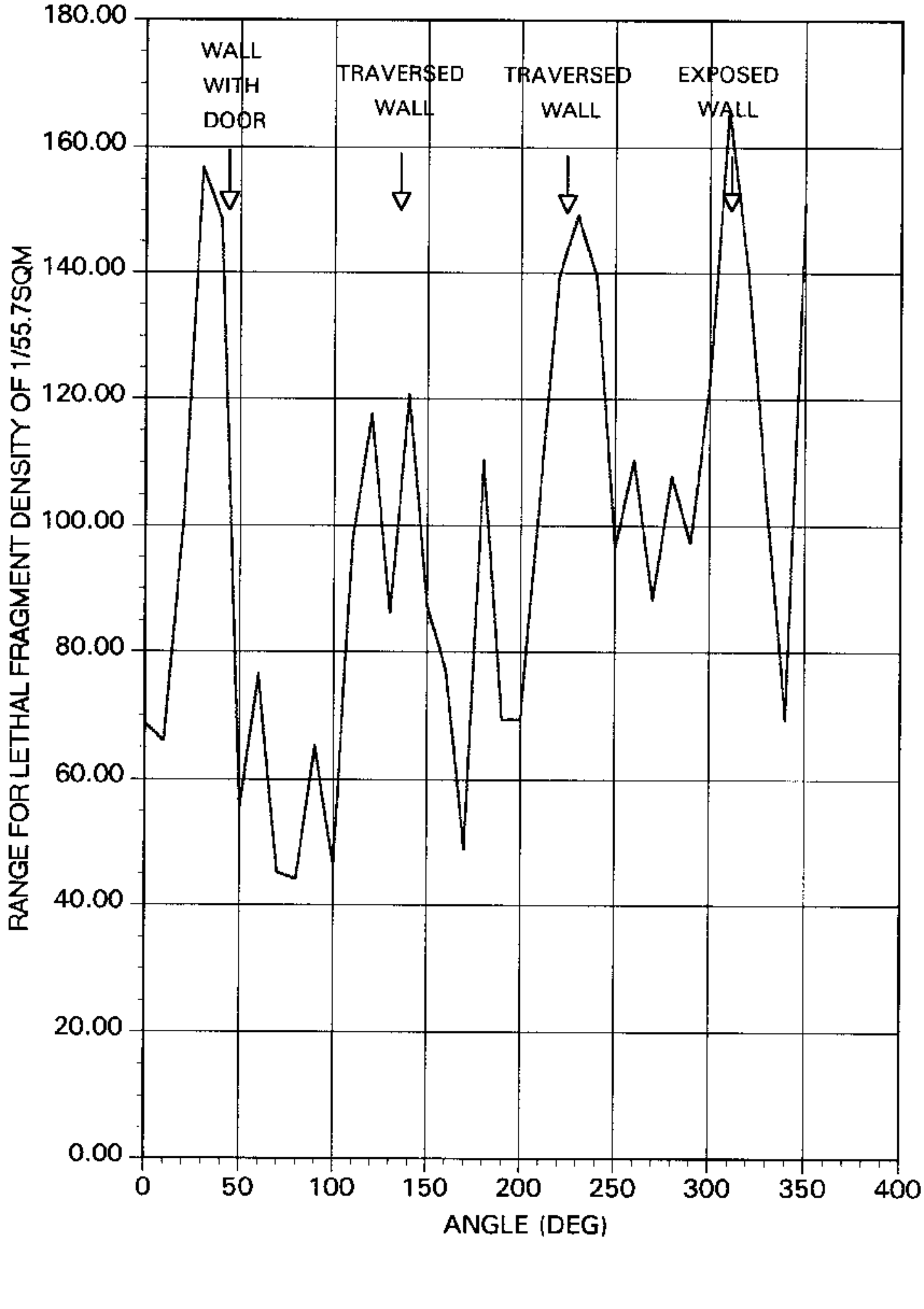

FIGURE 9 LOG10(MEAN FATALITY PROBABILITY) VS RANGE FOR SMALL QUANTITY TESTS 1 TO 6

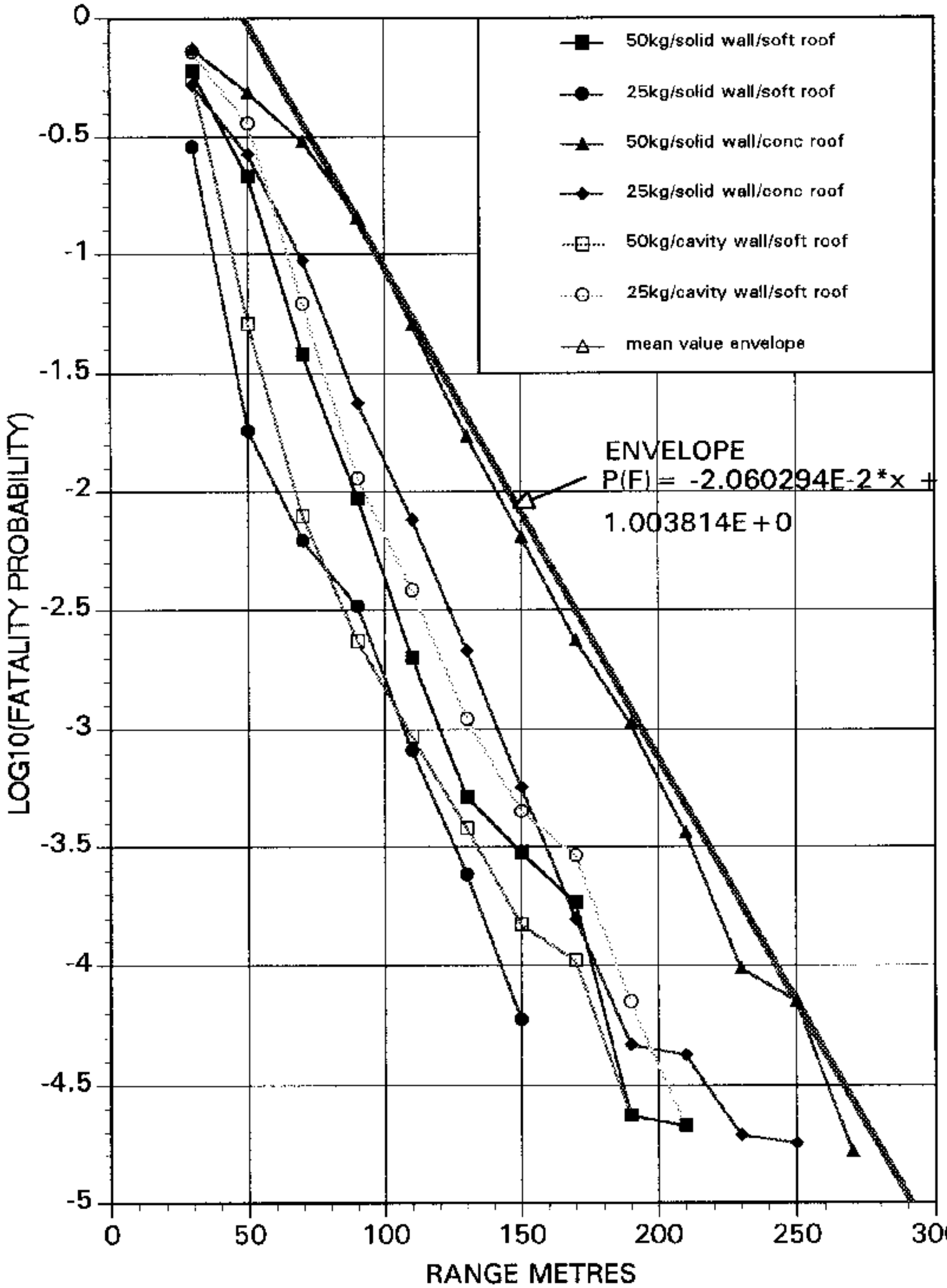

FIGURE 10 LOG10(PEAK FATALITY PROBABILITY) VS RANGE FOR SMALL QUANTITY TESTS 1 TO 6 TRAVERSED AND UNTRAVERSED

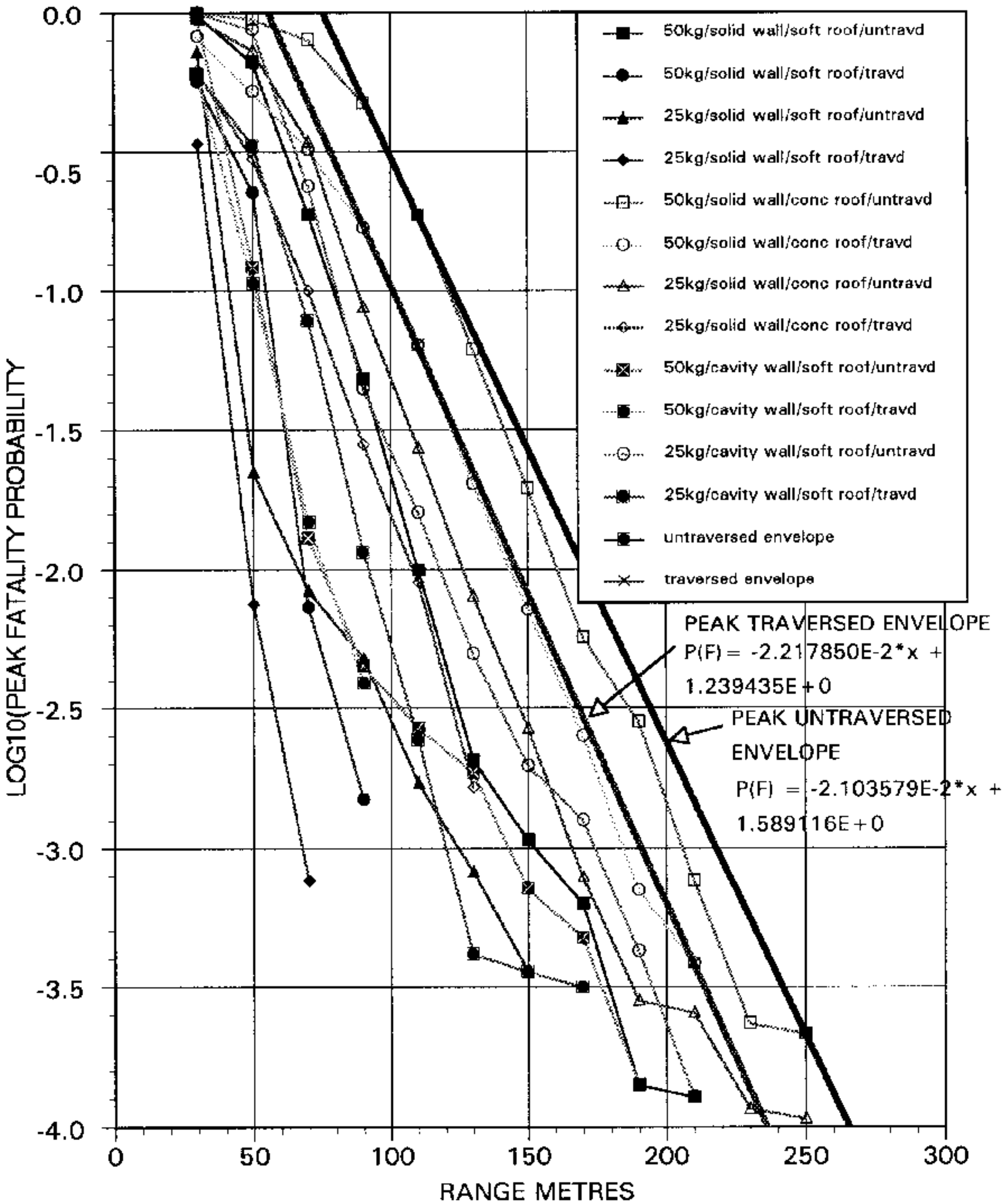

FIGURE 11 LOG(PEAK FATALITY PROBABILITIES) VS RANGE FOR SMALL QUANTITY TESTS 3 (50KG) AND 4 (25KG) IN CONCRETE ROOF BUILDINGS

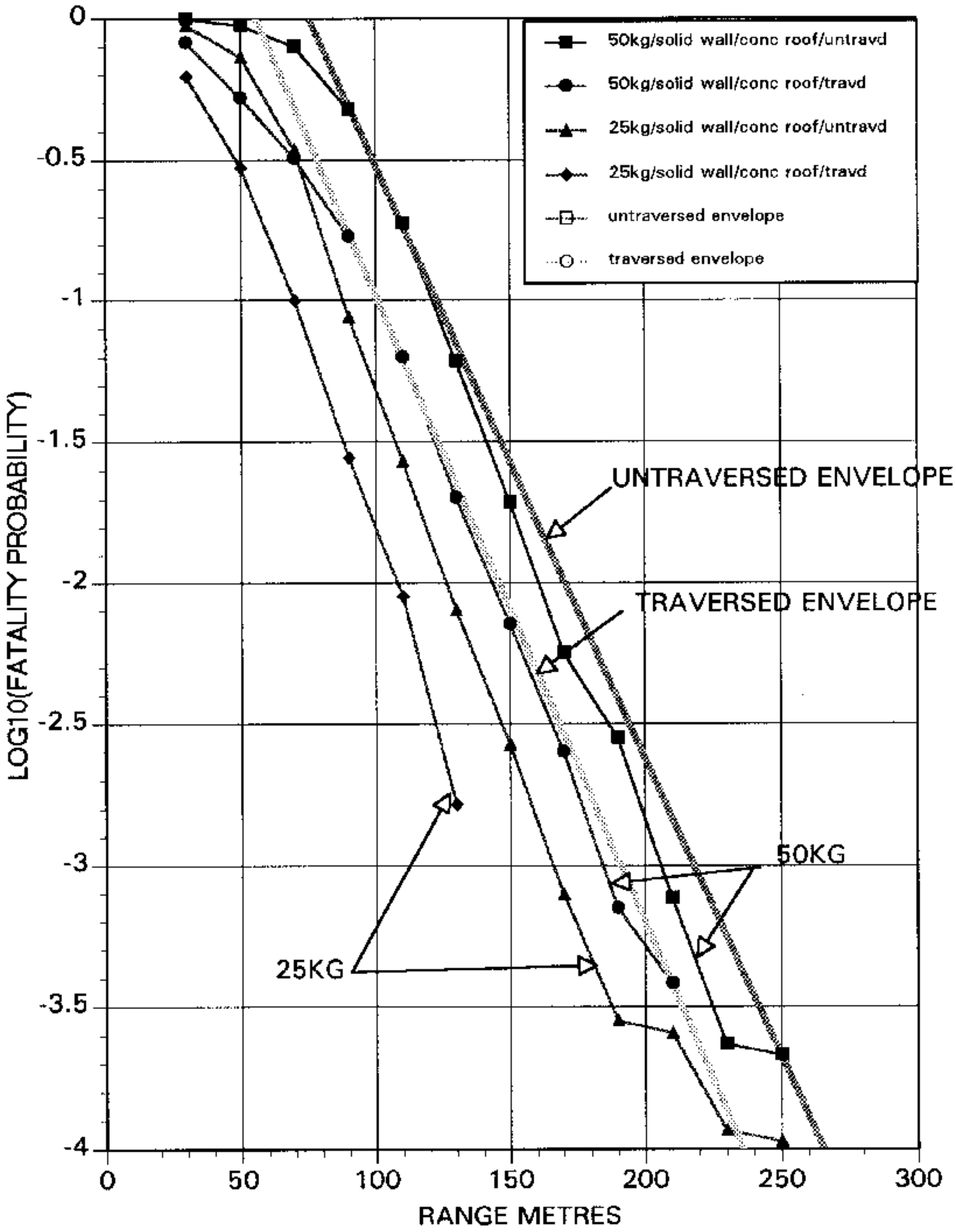

FIGURE 12 LOG(PEAK FATALITY PROBABILITY) VS RANGE FOR SMALL QUANTITY TESTS 1 (50KG) AND 2 (25KG) IN SOLID WALL, SOFT ROOF BUILDINGS

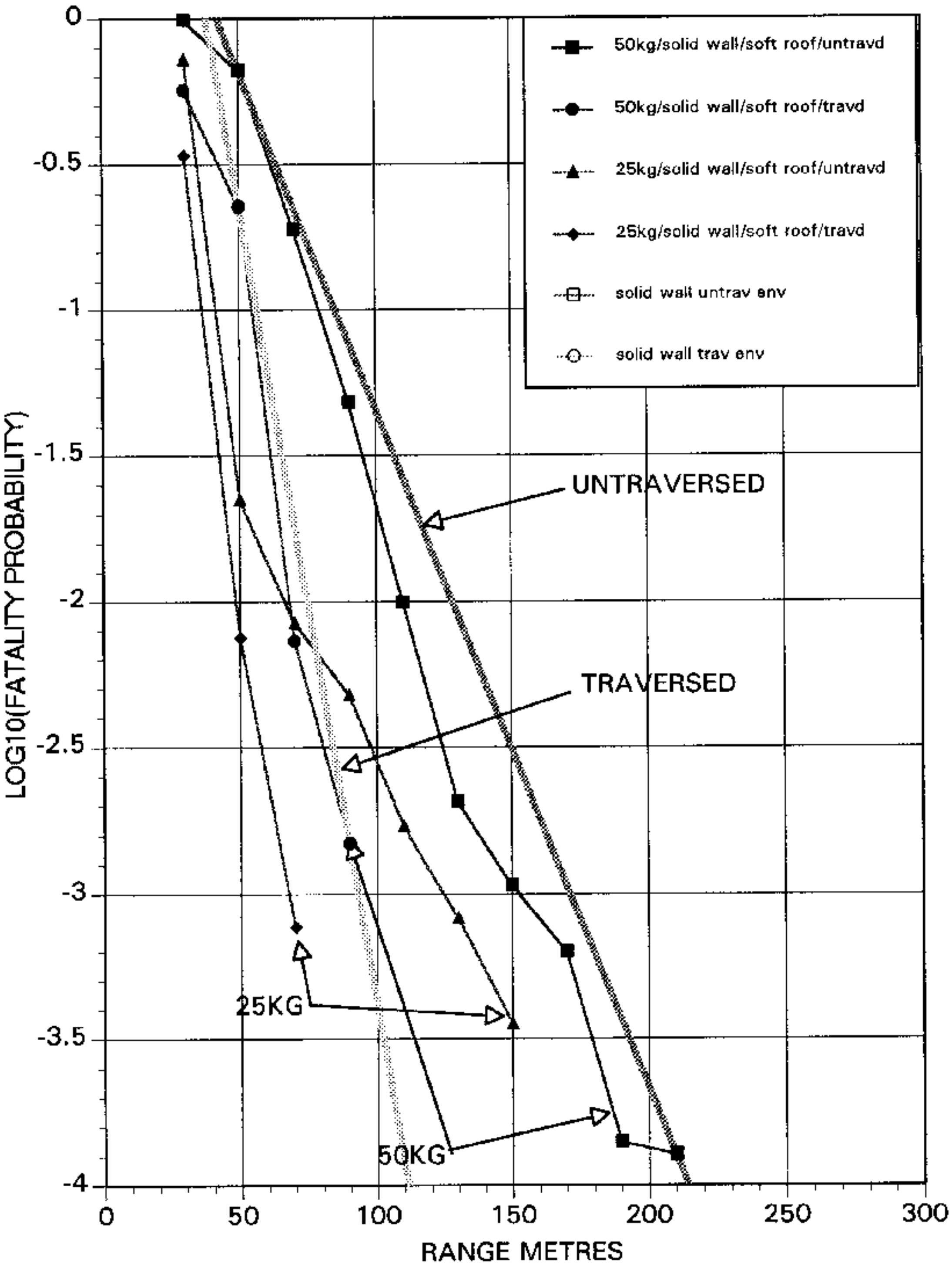

FIGURE 13 LOG10(PEAK FATALITY PROBABILITY) VS RANGE FOR 50KG TESTS 1 (SOLID WALL) AND 5 (CAVITY WALL) SOFT ROOF BUILDINGS

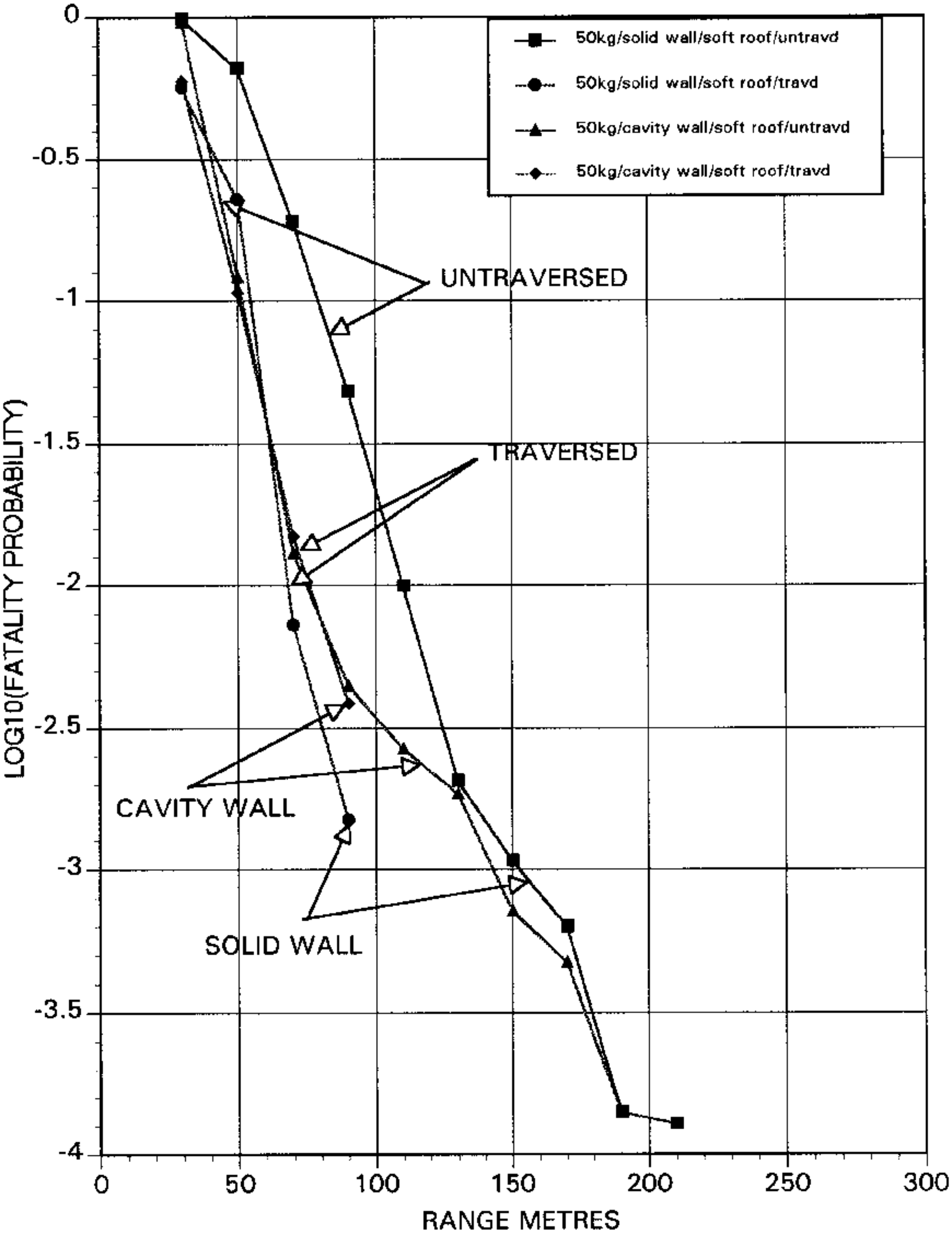

FIGURE 14 LOG10(PEAK FATALITY PROBABILITY) VS RANGE FOR 25KG TESTS 2 (SOLID WALL) AND 6 (CAVITY WALL) SOFT ROOF BUILDINGS

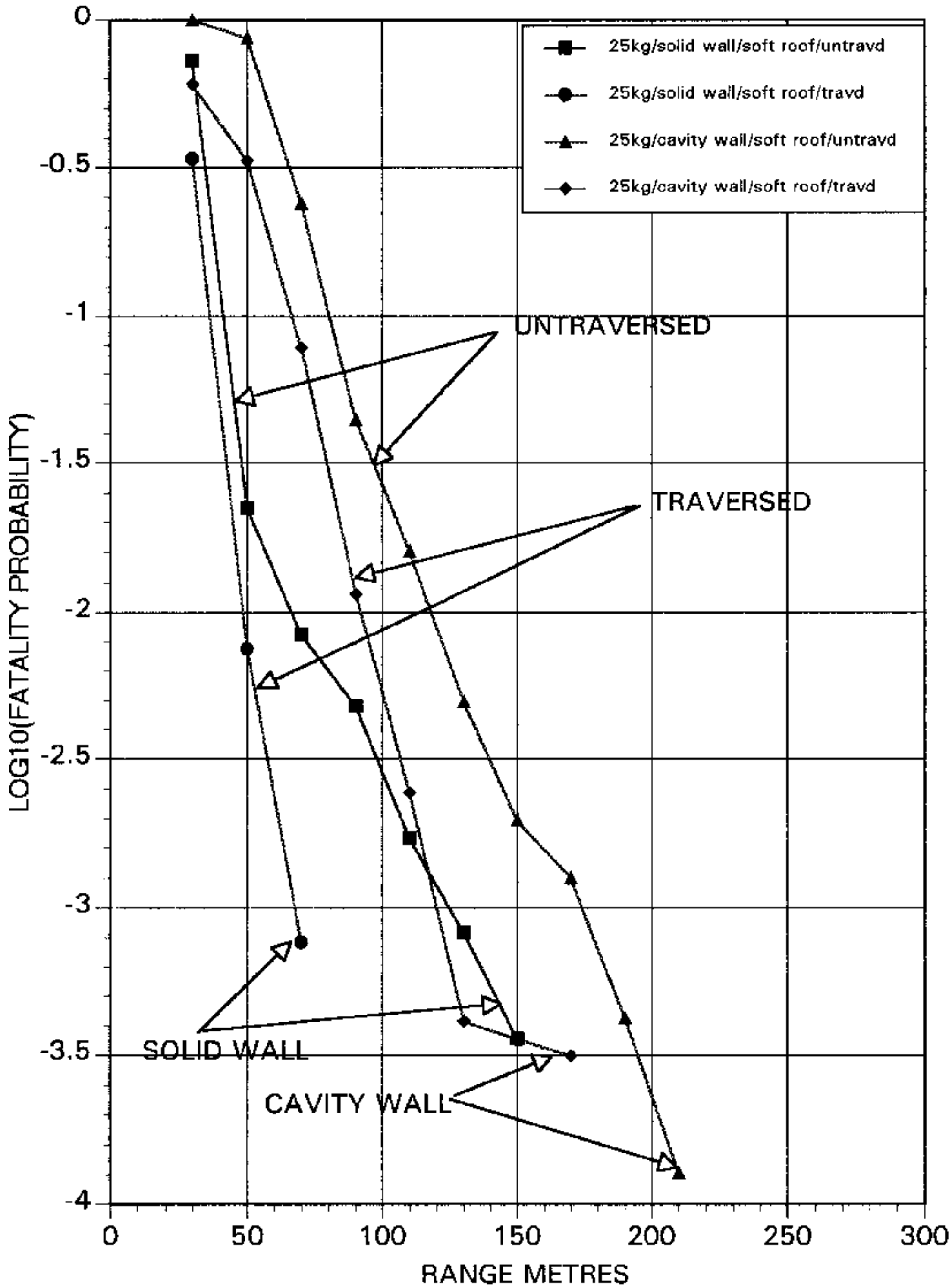

FIGURE 15 LOG10(PEAK FATALITY PROBABILITY) ENVELOPES VS RANGE FOR TRAVERSED AND UNTRAVERSED SOFT ROOF BUILDINGS

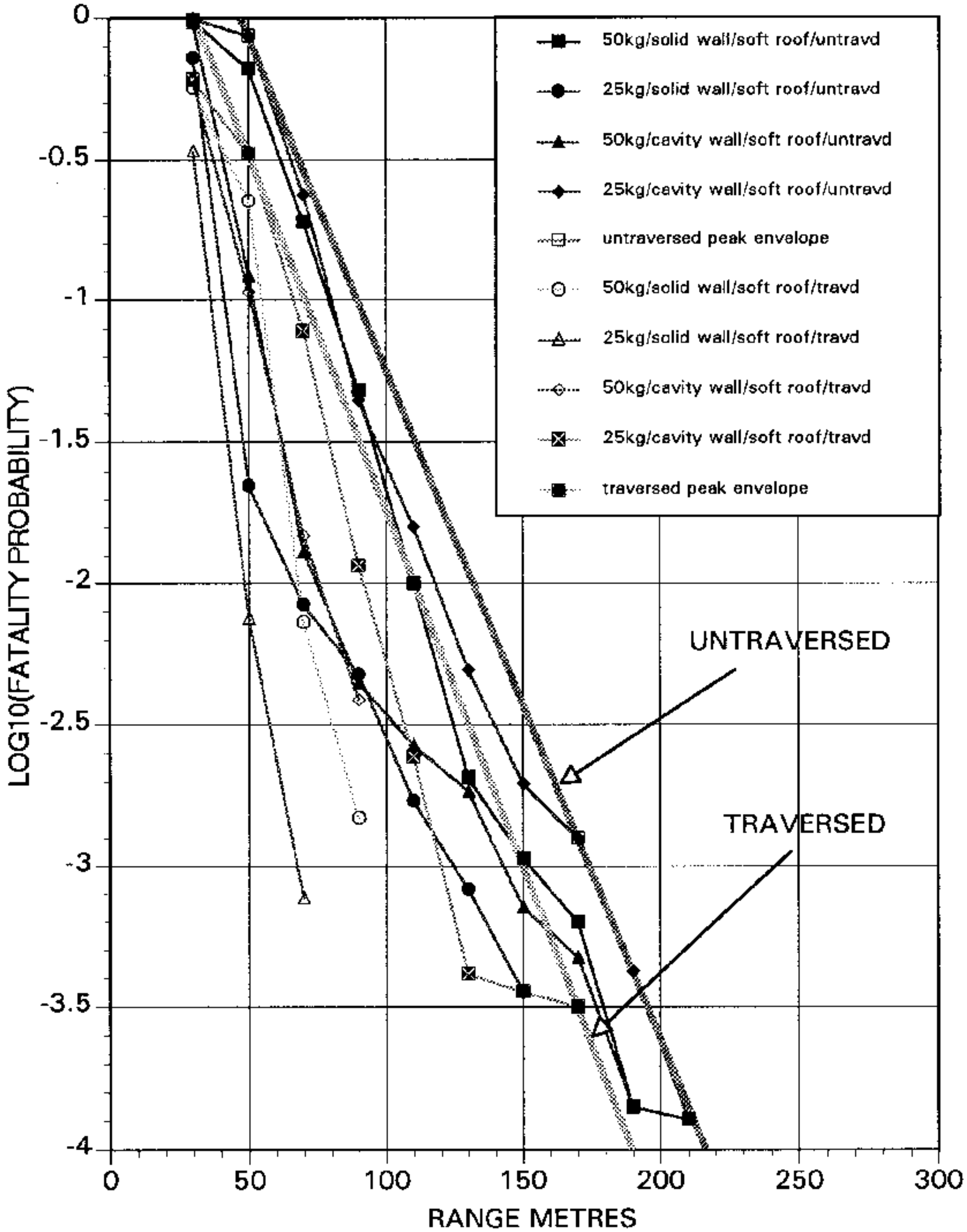

FIGURE 16 ENVELOPES OF LOG10(FATALITY PROBABILITY) VS RANGE FOR FRANGIBLE AND CONCRETE ROOF STRUCTURES